Electrical resistance tomography

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Electrical resistance tomography (ERT) is a method that calculates the subsurface distribution of electrical resistivity from a large number of resistance measurements made from electrodes. For in-situ applications, ERT uses electrodes on the ground surface or in boreholes. It is a relatively new imaging tool in geophysics. The basic concept was first described by Lytle and Dines as a marriage of traditional electrical probing (introduced by the Schlumberger brothers) and the new data inversion methods of tomography. Development of both the theory and practice of ERT was confined mostly to the late 1980s and the 1990s. Tomographic inversion added important new capabilities as it was more general, accurate, and rigorous at spatial imaging of geophysical electrical resistance data than earlier pseudosection or curve fitting methods.

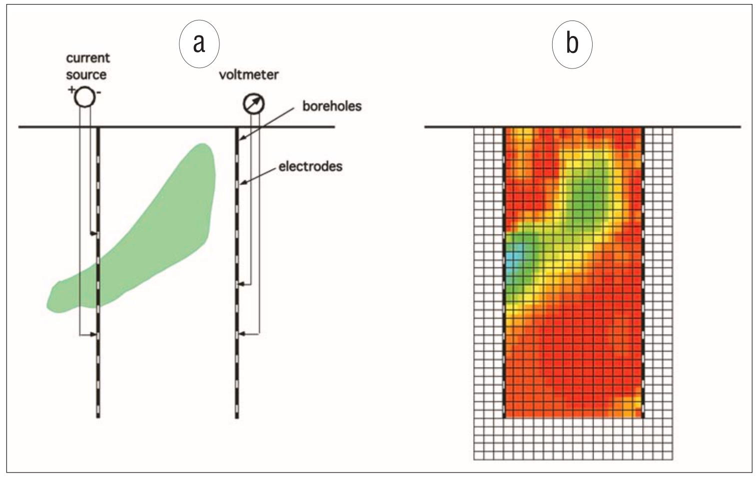

Figure 1. Schematic of ERT measurement and image reconstruction. (a) Electrode array and example for electrode measurement for cross borehole ERT. Electrodes may be in boreholes, on the surface or both. (b) Illustrative reconstruction of ERT image, showing discretization of space into model parameters.

An early application of geophysical ERT was to image laboratory core samples under test but practical field scale use of ERT was delayed by the lack of suitable measurement and test equipment. ERT requires the same four electrode resistance measurement used by the Schlumberger brothers (two electrodes to inject current and two other electrodes to measure the resulting potential); however, tomography requires addressing tens or hundreds of electrodes and making hundreds or thousands of such measurements in a timely fashion. Clearly, the available manual measurement systems that were designed for one, or perhaps a few measurements at a time, were not practical for ERT. High-speed, automated systems were needed.

The first system for practical application of geophysical ERT was constructed at Lawrence Livermore National Laboratory by two of the authors (Daily and Ramirez) in 1989. This system combined a commercial geophysical resistivity instrument (capable of producing the switched dc signal and making the synchronous voltage measurement), a commercial multiplexer capable of connecting the resistivity instrument to 20 electrodes and a computer to control the process and archive the data. The system was much faster than manual data acquisition and eliminated electrode connection and data transcription errors. Today, measurement systems are commercially available that are 10-20 times faster (up to a few thousand measurements per hour) and that can simultaneously address hundreds of electrodes.

Following the development of robust inversion routines and suitable data acquisition systems, ERT was applied to a wide range of environmental and engineering problems including the monitoring of vadose zone water movement, steam injection, and air sparging. Earlier applications concentrated on dc resistivity imaging. More recently, extensions that allow treatment of resistivity as a complex (real and imaginary) value have been developed. This has been driven by experimental observations of relationships between complex resistivity and both lithology and pore fluid contamination.

ERT applications are not constrained to near-surface investigations, however, and may be appropriate, in some cases, for characterization of oil reservoirs, for example. There is no technical reason why electrodes cannot be installed in a deep oil reservoir—say to monitor a secondary recovery mechanism like a steam flood. The installation of electrodes deep in a reservoir can be done cost effectively during the completion of production/injection wells. It is also worth noting that an innovative idea is currently being tested for using ERT to monitor fluid flow in deep formations using steel casings as very long electrodes. It is not the intent of this paper to argue the merits of these propositions, however. We aim to summarize key aspects of the technology and to explore its strengths and limitations.

Data acquisition—methods and hardware. In ERT, four electrodes are used to make the measurement to minimize the effect of contact resistance at the interface between the soil pore water and the electrode. A known current is forced between two electrodes and the potential difference is measured across the other two electrodes. Electrodes may be installed in any geometrical pattern, for example on the ground surface or in boreholes. Figure 1a illustrates the concept of ERT measurements, in this case for imaging between two boreholes. A number of four electrode measurements are required in order to "scan" the area or volume under investigation. Once these are obtained, inversion tools may be employed to determine the image of resistivity that best matches the set of measurements (as illustrated in Figure 1b). We discuss later the concepts of such inversion approaches.

Editor's note: This paper is a condensation of a review titled "Electrical resistance tomography—Theory and practice," to be published in Near Surface Geophysics, vol. 2, *D. Butler, ed., by SEG in 2004.* *See page 472 for a case study on this topic.*

To obtain the large number of independent impedance measurements necessary for tomographic inversion, ideally all possible linearly independent combinations from an array of electrodes are used. For n electrodes there are $n(n-3)/2$ such combinations. These combinations can be obtained using various strategies. One popular approach uses a pole-pole measurement scheme where one remote electrode (located far from the other electrodes) is used as one current pole and another remote electrode is used as a voltage reference pole. The two other poles, one for current and one for potential, are used in all the combinations possible in the array. For n electrodes in the array (not including the remote electrodes) there are $n(n-1)$ transfer resistance measurements. Only half of these are linearly independent because when the current source and voltage electrodes are interchanged the measurements are reciprocal (defined below) and, except for nonlinear effects, should be identical. Another approach is the dipole-dipole measurement scheme, where two electrodes are used to inject current, and two electrodes are used to measure a differential potential. Again, all combinations are usually taken, and half of these are reciprocal.

A very large number of other measurement schemes are possible, some of which have been found useful (i.e., Schlumberger and Wenner arrays for surface electrode surveys). There has been some discussion about the relative merits of these sampling schemes regarding sensitivity patterns for various electrode configurations. However, we believe that the concept of a "universal" measurement scheme for ERT (the best in all situations) is probably not achievable.

Another important consideration is measurement error. It is critical that measurement error be considered in any analysis. Errors are generally not random, and data inversions are strongly dependent on the errors. Furthermore, measurement errors will be strongly dependent on the environment to which ERT is applied and sensitivity and resolution will depend on the resistivity structure itself. At this time we are certain of two things about measurement error and sampling schemes:

1) It is important to sample the electrode array to obtain all the linearly independent data. This has been achieved when any additional measurement can be constructed by linear superposition of measurements already taken.
2) It is important to sample the array to obtain each measurement and its reciprocal. A reciprocal measurement is made by interchanging the electrode pair used for voltage measurement with the electrode pair used for current injection. The transfer impedance for these two cases will be identical if the system is responding linearly (i.e., according to Ohm's law) and there is no measurement error. Therefore, a comparison of a measured resistance and a reciprocal provides an estimate of data error that is a more reliable indicator of error than repeatability. The importance of having a good estimate of this error cannot be overstated. Because of the statistical nature of the more sophisticated and reliable inversion algorithms, it is better to have higher data errors that are well characterized than have lower data errors and not know their magnitudes.

ERT electrodes may be placed on the surface, in boreholes or both. Early work involved cross borehole measurements using electrodes placed into two or more boreholes. Later, other modalities quickly evolved including single borehole, borehole to surface, surface only, and all combinations of these possibilities. Possible sampling combinations are usually limited by the cost of electrode installation and the flexibility of numerical modeling codes. However, sometimes the sampling scheme is limited by the dynamic range of the measurement system or by physical constraints such as surface conditions (e.g., buildings, steel structures ruling out remote electrodes or asphalt ruling out surface electrodes).

The basic components of any acquisition system are: transmitter or current source; receiver which measures the resulting electrode potentials; multiplexer for quickly and automatically connecting the electrodes to the transmitter and receiver; and a computer for system control and data archival.

Data processing. In order to calculate a resistivity image from ERT data it is necessary to carry out an inversion that produces a model (that is, a spatially varying distribution of resistivity) that gives an "acceptable" fit to the data and satisfies any other prescribed constraints. We may start from the view that an objective function defines how well the model would reproduce the field measurements subject to a level of uncertainty in the data. Thus, the numerical procedure requires three elements: a forward model (usually a 2D or 3D finite element or finite difference formulation) for which we can compute the transfer impedances; an objective function which states the model fitting criteria that will be adopted and a search algorithm which determines the way in which the "optimum" resistivity model is found.

To begin the inversion, a starting model (for simplicity it is usually uniformly resistive) is chosen. Then, the forward model of that initial guess yields transfer impedances that are compared to the measured data. If the fitting criterion is met then this initial model is declared to adequately represent reality and the search is terminated. However, if the fitting criterion is not met then the model is adjusted so that the next model will have transfer impedances that are closer (in a least squares sense) to those measured. The search algorithm ensures that this step results in a better model than the previous model. The fitting criterion is applied again using these new transfer impedances. If the criterion is met, the process is terminated; otherwise it continues. Clearly, this is an iterative procedure and when the process reduces the objective function to a predetermined target value, we have an "optimal" model.

One of the main strengths of ERT is that resistivity is dependent on hydraulic, chemical, and thermal conditions in the subsurface. Thus, monitoring natural or artificially induced changes in resistivity can often provide valuable information about subsurface flow and transport processes. To assess changes in ERT images with time it is clearly possible to simply carry out independent data inversions, each representing a snapshot by the "impedance camera" at different times during the processes. By subtraction of pixel values from some reference, or background, image changes are easily computed. However, in many cases changes may be very small in comparison with the natural spatial variability within the region of interest. A cross-borehole survey in near-surface sediments may reveal contrasts over several orders of magnitude, for example, whereas an increase or decrease in saturation in the vadose zone, say, due to some process may change the resistivity by only a few percent. Since the inversion process is strongly influenced by data errors, the subtraction of independent images may then reveal little about the process of interest. To image small changes in a background of large contrasts attempts have been made to invert for changes in resistivity using coupled data sets.

A common approach utilizes a ratio of two impedance data sets in the inversion. In this method, a new data vector, $\mathbf{d}_r$, is formed from:

$$\mathbf{d}_r = \frac{\mathbf{d}_t}{\mathbf{d}_0}\mathbf{f}(\sigma_{\text{hom}}), \tag{1}$$

where $\mathbf{d}_0$ is the data vector at some reference state, $\mathbf{d}_t$ is the data vector at some time t and σ_{hom} is an arbitrarily chosen homogenous conductivity.

Inversion of the new data set $\mathbf{d}_r$ in the normal manner then results in an image that will reveal changes relative to the reference value σ_{hom}.

This "ratio" approach has proved to be invaluable for many ERT applications, in particular when 2D inversions are applied to 3D problems. For example, borehole effects due to overly conductive or resistive backfill around the electrodes, commonly observed in images of cross-borehole data, are often removed by such a procedure. More importantly, however, very subtle subsurface changes can be imaged using this approach.

Case history—tank leak detection and leakage plume imaging. We now present a case history to illustrate the value of ERT for subsurface imaging. This example is intended to be only representative of the investigations where the method has been successfully used. The example has been selected to illustrate both temporal and spatial resolution and show a typical environment (near surface) and process (fluid infiltration) to which ERT has been successfully applied.

One of the most difficult tasks for the U.S. Department of Energy (DOE) is the clean up of environmental hazards left over from the cold war. An example of this is the very technically challenging remediation of the large underground tanks used to store both chemically toxic and radioactively dangerous byproducts of nuclear weapon production. Currently there are 177 of these tanks at Hanford in southeastern Washington and another 51 at Savannah River in western South Carolina. In addition, there are tanks at Idaho National Engineering Laboratory, Idaho, and Oak Ridge, Tennessee.

The task of detecting leaks from these tanks, during their normal lifetime or during remediation, is a particularly challenging task because of the nature of the tank contents. Simple liquid level sensors are difficult to use because the waste varies in consistency from liquid to paste to solid—sometimes all mixed together in the same tank. A leak detection method currently in use senses gamma rays from any radioactive contaminant plume as it forms outside the tank. Detectors are lowered into boreholes drilled for this purpose near some of the tanks. However, even the more energetic gamma rays travel less than a meter in soil so many boreholes are required to sample even one tank (typically 23 m in diameter) and it is particularly difficult using boreholes around the sides of a tank to detect leaks from the bottom-center of a tank. However, because any leaking waste changes the electrical conductivity of the soil, measurements from around the periphery of the tank could be used to detect and image a conducting plume even if it was located under the tank.

To test this idea, an experiment was conducted at the Hanford Reservation, near Richland, Washington. A facility was built to simulate, as closely as practically possible, conditions in an underground storage tank farm at Hanford. The strategy was to release a surrogate tank waste from the mock tank and use ERT to detect and to image the release. With such an arrangement, performance of the method was tested under realistic conditions. Several release points were built into the mock tank so that fluid could be released at a controlled rate into the soil. These release points were located near the edge, to simulate "bathtub ring" corrosion holes, as well as points nearer the center to simulate corrosion holes in the bottom seams.

An array of 64 electrodes was installed in boreholes around the mock tank, and ERT was used to map the 3D electrical resistivity distribution under the tank to a depth of 10.7 m (the deepest electrode). The diametrical distance between the electrode arrays was 20.7 m.

From the extensive results of this test we have chosen a small sample of results to illustrate some of the useful properties of ERT. Results from three of the release sequences in the test are shown in Figure 2. It is evident that ERT was able to detect each of the conductive anomalies produced by these simulated tank leaks. Each release point was at a different location, and each produced a plume showing the shape and extent of the zone invaded by the surrogate fluid. It appears that each release produces a separate and distinct plume. In fact, the plumes overlap and are separated only because a different baseline is used for each image. The results suggest that having a tomographic reconstruction of the plume means that a straightforward and intuitive interpretation is appropriate. This is so because of the truly 3D nature of ERT and because there is a simple (although nonlinear) relationship between conductivity, pore fluid volume, and ionic strength. ERT is truly three-dimensional because all electrical current paths influence the reconstruction, whereas for wavefield tomography like radar or seismic, only the rays connecting the source and receiver influence the reconstruction.

Not so evident from these results is the fact that ERT is especially valuable for long-term process monitoring, particularly when onsite measurement equipment can be controlled by an offsite operator. A time series of any of these three separate events would show the growth and movement of the plume. Reservoir production could be thought of as a long-term process and a 3D image of that process could be of high value to the reservoir engineer wishing to know details such

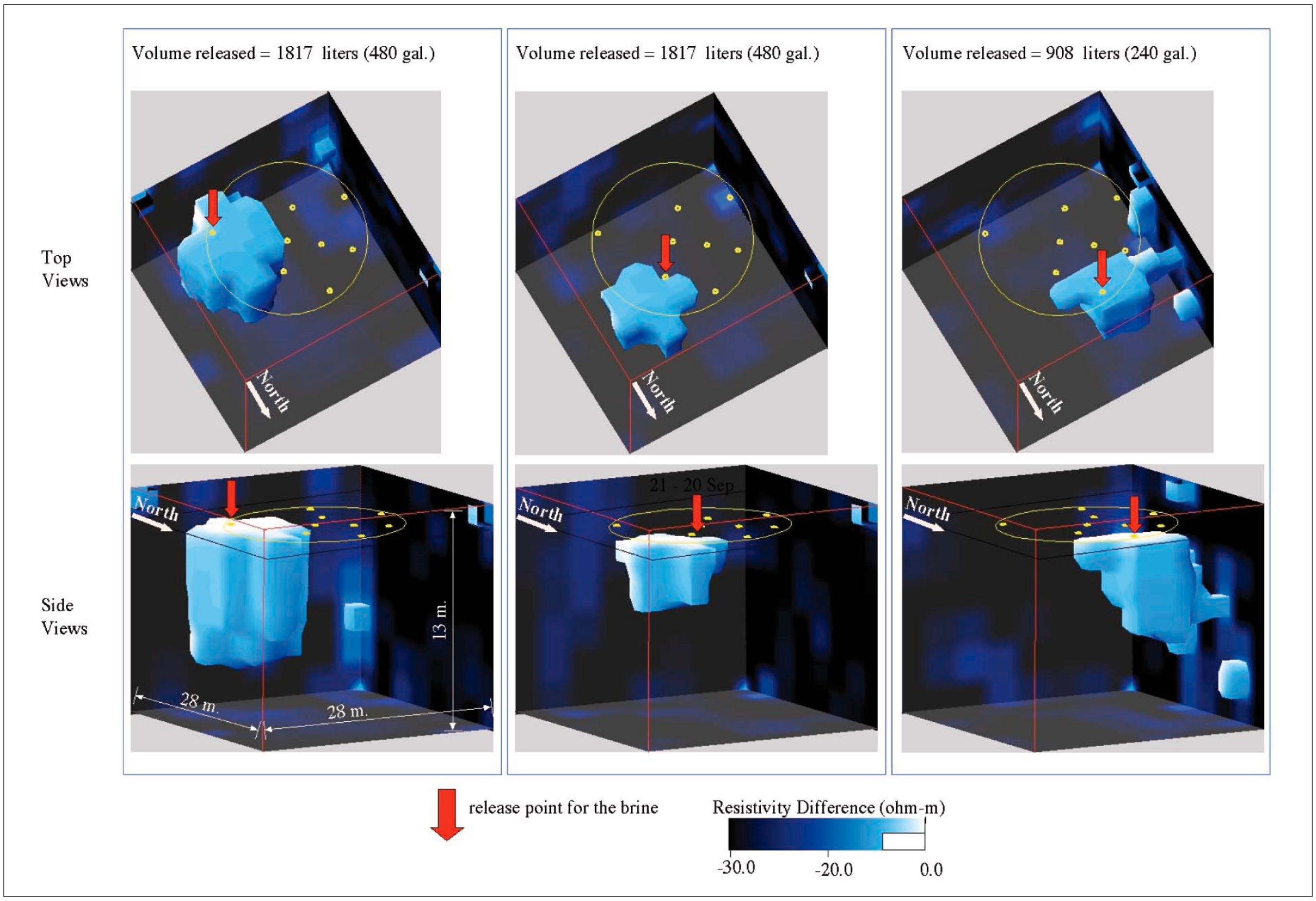

Figure 2. 3D ERT images showing changes in resistivity at three selected days from the test. For each case the upper image is a top view and the lower image a side view with the tank footprint and fluid release points superimposed. The isosurface defines the volume where the resistivity changed by more than 10 Ohm m.

as where production is coming from and where it is not coming from. Long-term imaging of a reservoir could provide such information. This is especially true because electrical imaging is especially sensitive to pore fluid content. Almost all the current used to create an ERT image flows through the pore fluid, not through the silicate matrix. Therefore, small changes in pore fluid conductivity produce large changes in bulk formation conductivity.

Practical application of ERT. The case history is a typical example of a successful ERT project. We recognize that there have been failures as well. What makes the difference between success and failure? The answers to this question are important because they identify the components required for a successful ERT project. We list here some guiding principles that will help increase the probability of success with ERT:

1) The ERT inverse process is typically underdetermined so that more data is better than less data, provided the errors are known.
2) It is better to know the errors in the data than to have lots of data with uncertain errors.
3) A comparison of repeated measurements, despite this being a very popular approach, will not produce a good measure of data errors. Reciprocity is a much better measure of data error.

4) An accurate forward solver and a fine mesh discretization are very important. The problems from inaccurate forward solutions can be subtle and create artifacts (modeling errors may be greater than measurement errors).
5) There is no strong evidence that any particular measurement scheme is superior. Several schemes have been used and compared, but it is likely that other factors (such as data error) dominate the reconstruction quality.
6) A variety of experimental problems can degrade image quality. A common one is high electrode contact resistance resulting from installing electrodes in a borehole and filling the hole with dry sand. The ideal fill material will match the native soil conductivity.
7) Because ERT requires high-speed data collection on a large array of electrodes, the ideal electrode is inexpensive, rugged, long lasting, nontoxic, and electrically quiet (nonpolarizing).
8) Care must be taken to avoid electromagnetic effects that violate the electrostatic approximation made in the forward model.

Strengths and weaknesses. Often several geophysical methods are used together, each lending its strengths to the problem at hand. We believe that electrical resistance tomography will be used increasingly in this mode because it offers some unique capabilities. We list here some of the strengths and weakness of ERT to help put the method in geophysical perspective. First the strengths:

1) Because it is not necessary to move the sensors, ERT can be easily automated. Multiplexing of electrodes into an array of voltmeters, control of electronics, data storage and transmittal, and even data processing to a reconstructed image are all easily accomplished automatically under computer control. In fact, various parts of this automation have already been accomplished for long-term monitoring of steam injection.
2) ERT surveys can be carried out remotely. One such system that has been tested by the authors uses satellite communications to remotely control a field measurement system. This system reduces to a minimum the need for site visits thereby allowing frequent, cost-effective surveys.
3) Recent developments in computer technology as well as inversion algorithms have led to fast ERT data processing.
4) Commercial data acquisition systems are now available at reasonable costs making ERT within the reach of universities and small geophysical service companies.
5) ERT imaging of galvanic electrical properties is a good complement to other geophysical methods. Resistivity is especially sensitive to porosity, pore connectivity, and to the amount and ionic strength of pore fluids. It is therefore a good complement to seismic velocity measurements that are very sensitive to lithology type and overburden pressure.

ERT also has limitations:

1) At the low frequencies required for the electrostatic approximation, physical contact is required between the ground and the electrodes.
2) Tomography requires interrogating the target from as many "views" as possible. Geophysical tomography, therefore, often requires drilling or pushing boreholes which are expensive and invasive.
3) Probably the most disappointing attribute of ERT is its low spatial resolution.

Unlike ground-penetrating radar or controlled-source electromagnetic sounding, ERT is a relatively new technology. Off-the-shelf hardware and robust software are becoming available but user experience is still important for successful results. However, many groups, with both private and public support, are working to make ERT more user-friendly and more widely available. Considerable progress has been made. It is noteworthy, however, that 24 years ago Jeff Lytle and Kris Dines (the original developers of ERT) stated research and development goals for ERT that are relevant even today. They noted in their pioneering paper on the "impedance camera":

> "Items worthy of future research include an assessment of the influence of noise in the data, a study of the accuracy of the reconstruction and its spatial dependence, an evaluation of the degree of dependence of various measurement configurations, an analytic study of the resolution limit, and a determination of the extent to which the use of a priori knowledge affects the interpretation."

Many of these topics still deserve our attention and continue to be worthy research areas.

Suggested reading. "Electrical resistivity tomography of vadose water movement" by Daily et al. (*Water Resources Research*, 1992). "Crosshole IP imaging for engineering and environmental applications" by Kemna et al. (GEOPHYSICS, 2004). "The effect of noise on OCCAM's inversion of resistivity tomography data" by LaBrecque et al. (GEOPHYSICS, 1996). "Inversion of induced polarization data" by Oldenburg and Li (GEOPHYSICS, 1994). "Detection of leaks in underground storage tanks using electrical resistance methods, (UCRL-JC-122180, October, 1995)" by Ramirez et al. (*Journal of Engineering and Environmental Geophysics*, 1996). "Monitoring and underground steam injection process using electrical resistance tomography" by Ramirez et al. (*Water Resources Research*, 1993). "3-D resistivity forward modeling and inversion using conjugate gradients" by Zhang et al. (GEOPHYSICS, 1995). TLE

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